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# Development of a hydrology and water quality model for a large transboundary river watershed to investigate the impacts of climate change – A SWAT application

Natalja Čerkasova[a,*,1], Georg Umgiesser[b,a], Ali Ertürk[c]

[a] Marine Research Institute, Klaipeda University, Klaipeda, Lithuania
[b] ISMAR-CNR, Institute of Marine Sciences, Venezia, Italy
[c] Istanbul University, Faculty of Aquatic Sciences, Department of Marine and Freshwater Resources, Division of Freshwater Resources and Management, Istanbul, Turkey

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ABSTRACT

The aim of this study is to assess a different approach of SWAT model setup with enhanced Hydrologic Response Unit (HRU) definition procedure. The method uses a set of customizable MATLAB scripts (hence, SWAT-LAB) to produce HRUs from a combination of topographic, soil, landuse and administrative unit rasterized datasets. We used this approach to setup, run and calibrate a large-scale transboundary Nemunas River model, consisting of eleven sub-models. Nemunas River is the major contributory that discharges into the Curonian Lagoon, which is the largest European coastal lagoon. Belarus, Lithuania, Poland and the Russian Federation Kaliningrad Oblast share Nemunas River basin area. The basin is experiencing nutrient load from different sources in the riparian countries, nevertheless, the burden of improving the water quality of the river falls mainly on Lithuania. This article focuses on assessing the practicability of SWAT-LAB for creating a high-resolution large-scale transboundary hydrological and water quality model, where data availability is limited and fragmented. We demonstrate the model performance on a case study of one of the Nemunas River tributaries: Neris or Vilija River basin, which is situated largely in the Republic of Belarus. Model performance was evaluated graphically, using hydrographs and percent exceedance curves, and quantified using coefficient of determination ($R^2$) and Nash–Sutcliffe efficiency (NS). We achieved good model performance for monthly (calibration $R^2 = 0.80$, NS = 0.83; validation $R^2 = 0.80$, NS = 0.76) and daily (calibration $R^2 = 0.66$, NS = 0.66; validation $R^2 = 0.67$, NS = 0.66) flow. Satisfactory performance results were achieved in modeling monthly loads of suspended sediments (calibration $R^2 = 0.4$, NS = 0.44; validation $R^2 = 0.58$, NS = 0.34), total phosphorus (calibration $R^2 = 0.71$, NS = 0.61; validation $R^2 = 0.53$, NS = 0.56) and total nitrogen (calibration $R^2 = 0.55$, NS = 0.42; validation $R^2 = 0.48$, NS = 0.4). Furthermore, we use the model to assess possible future nutrient loads that could be transported from Belarus to Lithuania under two climate change scenarios (RCP 4.5 and 8.5) and present the results.

## 1. Introduction

The Curonian Lagoon, the largest coastal lagoon in the Baltic Sea and Europe as well, is facing severe eutrophication problem. Due to vast land use for agriculture and point source pollution, the amount of nutrients that enter the lagoon thru the rivers is substantial, which in turn is the main cause of the observed plumes. HELCOM Baltic Sea Action Plan (BSAP) is an ambitious program to restore the good ecological status of the Baltic marine environment by 2021 (HELCOM Ministerial Meeting, 2007). The Plan was adopted by all the Baltic coastal states and the EU in 2007. The vision of this plan is a healthy Baltic Sea environment, with diverse biological components functioning in balance, resulting in good environmental/ecological status and supporting a wide range of sustainable human economies and social activities (HELCOM Ministerial Meeting, 2007).

To reduce the eutrophication in the Baltic Sea, a Nutrient Reduction Scheme was adopted by the HELCOM member states (Bartnicki and Benedictow, 2017). HELCOM Nutrient Reduction Scheme is a regional approach of sharing the burden of nutrient reductions to achieve the goal of the Baltic Sea unaffected by eutrophication agreed by the Baltic

* Corresponding author.
*E-mail address:* natalja.cerkasova@gmail.com (N. Čerkasova).
[1] Postal address: Universiteto al. 17, Klaipėda 92295, Lithuania.

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**Table 1**
Country Allocated Reduction Targets for pollution from both land and air, in tons, agreed in 2013.

| | Nitrogen | Phosphorus |
|---|---|---|
| Denmark | 2890 | 38 |
| Estonia | 1800 | 320 |
| Finland | 2430 + 600* | 330 + 26* |
| Germany | 7170 + 500* | 110 + 60* |
| Latvia | 1670 | 220 |
| Lithuania | 8970 | 1470 |
| Poland | 43,610 | 7480 |
| Russia | 10,380* | 3790* |
| Sweden | 9240 | 530 |

Sea countries.

According to the Nutrient Reduction Scheme (Table 1), Lithuania has to achieve a reduction of Nitrogen input of 8970 tons, and Phosphorus – 1470 tons (Bartnicki and Benedictow, 2017). Up to this point, (May-2018) Lithuania has yet to make sufficient progress in land and fertilization management, nutrient recycling and rural water management to achieve substantial reduction for nutrients leeching thru the rivers into the Curonian Lagoon and subsequently – to the Baltic Sea. After the latest HELCOM ministerial meeting in Brussels (6th of March 2018) (Baltic Marine Environment Protection Commission, 2018), it became clear that the set nutrient reduction targets cant' be achieved with the current progress, so strengthening the implementation of the Baltic Sea Action Plan by 2021 was set as a top priority and includes adjusting the BSAP based on new knowledge and future challenges. Our conducted study aims to contribute to this endeavor, and provide more insight about the nutrient loads in one of the Baltic Sea subbasins – the Nemunas River basin.

Nemunas River is one of the biggest river systems in the eastern part of the Baltic Sea and the largest river in Lithuania, which contributes the most in terms of water, sediments and nutrients to the Curonian Lagoon. More than 90% of water and nutrient input to the Lagoon is provided by the Nemunas River (Pilipchuk et al., 2014). The rivers watershed is shared by Lithuania, Belarus, Poland and Russian Federation Kaliningrad oblast.

Several hydrological models (HBV, MIKE, etc.) were applied to the Nemunas River basin in different studies (Kriaučiunienė et al., 2008; Rimkus and Vaikasas, 2012; Stonevičius et al., 2017; Stuopis et al., 2010), assessing impact of different stressors on the system. SWAT (Soil and Water Assessment Tool) is used by Lithuania's Environmental Protection Agency in the development of methodic and modelling system of nitrogen and phosphorus load calculation for surface waters of Lithuania. However, none of the previous studies covered the entire Nemunas River watershed in assessing sediment and nutrient calculations.

To correctly identify the hydrologic regime in the watershed, a basin-scale model with sufficient accuracy was developed in previous studies (Čerkasova et al., 2016). This model was used to assess possible changes in the hydrologic regime of the Nemunas and Minija Rivers in the light of near-term climate projections derived from the IPCC AR5. It was found that the watershed system is sensitive to climate change and can lead to possible shifts in the hydrologic regime. As a continuation of previous studies, the Nemunas watershed model had to be updated to include nutrient transport in the system. A more detail representation of the watershed is needed to be able to simulate land management practices of different countries and different administrative units within the countries' subbasins.

One of the challenges of this study is that the upper river basins (48% of the total watershed area) are situated in Belarus, which is not an EU nor HELCOM member, thus data interchange between Lithuania and Belarus is very poor. On the other hand, National Statistical Committee of the Republic of Belarus releases official statistics of macroeconomic and environment, which is publicly available (National Statistical Committee of the Republic of Belarus, 2017). The National Statistical Committee uses administrative units as a basic cell for data gathering, so the majority of statistical data (like crop-yield, forestry, land management, fertilization, etc.) is available on an administrative unit level. This is an important issue for the hydrological and water quality model development, since usage of standard available modeling tools does not allow direct incorporation of administrative units. Thus, an advanced version of SWAT model setup was developed and used to produce Hydrologic Response Units (HRUs) which incorporate data from not only slope, landuse and soil data, but also the administrative unit grid, providing the flexibility to derive common fertilization practices, land management and crop yields with sufficient precision based on publicly available statistical data.

## 2. Data and methods

### 2.1. Model setup method

Some limitations and drawbacks of the standard model setup tools like ArcSWAT, MWSWAT, QSWAT ("ArcSWAT|Soil and Water Assessment Tool," 2012, "MWSWAT|Soil and Water Assessment Tool," 2012; Dile et al., 2017) were the main motivators for creating a different method for SWAT setup. As stated previously, SWAT is a comprehensive model requiring hundreds of model inputs for hydrological parametrization and watershed description some of which also vary according to land use and soil attributes. SWAT operates on text-based inputs only, the preparation of which manually would be an unproductive and cumbersome task. The details of SWAT input files are given by Arnold et al. (2012).

To ease the difficult task, numerous software tools (Danile, 2013; Dile et al., 2016; George and Leon, 2008; Olivera et al., 2006; Rathjens and Oppelt, 2012; Trotochaud, 2014; Wu and Liu, 2014, 2012) were developed for complete or partial SWAT input data set generation. Some of these software tools are GIS based and supported by form-based graphical user interfaces ("ArcSWAT|Soil and Water Assessment Tool," 2012; Dile et al., 2017; George and Leon, 2008), whereas others are based on scripting languages (such as Python or R).

The GIS/GUI based SWAT model input set generators are easier to use, however they are preprogrammed to specific datasets to generate a default SWAT parametrization. Some allow the usage of a lookup table for different and non-standard pixel values in user-supplied grids; however, the SWAT database table integrated into those user interfaces cause some limitations and are not always easy to extend.

Script based SWAT input set generators are relatively difficult to use and even more difficult to learn, but are more flexible in terms of automatic data generation (the user is not obliged to sit in front of a computer and do a mouse-click intensive input editing job) and even programmable to some extend (for example it may be possible to use "if" clauses when a specific condition related to data-layer combination is encountered) either directly or by modifying the underlying scripts.

In this study we chose to develop a script based SWAT input generator coded in MATLAB (hence, SWAT-LAB). The reasons for choosing a script-based approach for this study are listed below:

- European community based field database (such as CORINE, etc.) are not available for the entire case study area;
- Field data such as land-use and soil had to be compiled from many different sources and standard GIS preprocessing techniques were not sufficient in a practical manner;
- Nutrient emission based data were available based on administrative boundaries rather than sub-watersheds so in order to distribute the emissions on SWAT-HRUS, HRUs needed to be based on administrative units as well.

We chose MATLAB as the main development platform because:

- It contains a high-level programming language equipped with many functions that fulfill the otherwise algorithmically difficult programing tasks (such as sorting, finding out the unique values in multidimensional arrays);
- Importing of raster data (such as geotiffs) and table based data (such as Excel Worksheets) is very easy and straightforward within scripts;
- It allows the user to build complicated data structures fairly easy;
- It is naturally vectorized and therefore lets the programmer to avoid for-loops that are inefficient in terms of computational performance;
- It is equipped with a Just In Time (JIT) compiler that reduces the runtime for repeated function calls drastically.

The SWAT-LAB scripts automate the steps of the SWAT model setup, starting from HRU definition and ending with full model setup, except some of the watershed-scale setup files (atmo.atm, basins.bsn, basins.wwq, crop.dat, fert.dat, file.cio, pest.dat, septwq.dat) that can be altered manually. The watershed delineation process has to be performed using any GIS tool, prior to the HRU definition process. In this study, we used ArgGIS ArcHydro tools to perform the delineation. Further, ArcGIS was used to pre-process the DEM, Landuse, Soil and administrative unit maps.

A novel method was developed for HRU definition of the SWAT model. The method incorporates a standard procedure of lumping grids of the landuse, soil and slope maps and, in addition, includes administrative unit grid (Fig. 1). The reasoning for this is to achieve a better spatial representation of diffused pollution loads and to simplify large-scale high-resolution model setup management and parametrization procedures. More details on the method are given in Appendix A.

The model development followed the workflow:

1. Model division into sub-regions (sub-models);
2. Initial processing of the DEM, River network, Reservoir and Lake/pond, monitoring grids for each region (projections, grids, etc.);
3. ArcHydro/ArcSWAT delineation for each region;
4. Semi-automatic processing of the maps (subbasin grid, landuse, soil, administrative units, weather processing for each region using developed ArcGIS models);
5. Preprocessing of the input databases (Excel worksheets);
6. SWAT-LAB setup;
7. Running SWAT-LAB to generate HRUs for each region (PASS 1);
8. Running SWAT-LAB to generate all the input files for SWAT (PASS 2 and Waterbody), in accordance with the SWAT documentation (Arnold et al., 2012);
9. Running SWAT for each region;
10. Standard procedures for manual model calibration and validation for each of the regions, using SWAT-LAB to change the desired parameter values.

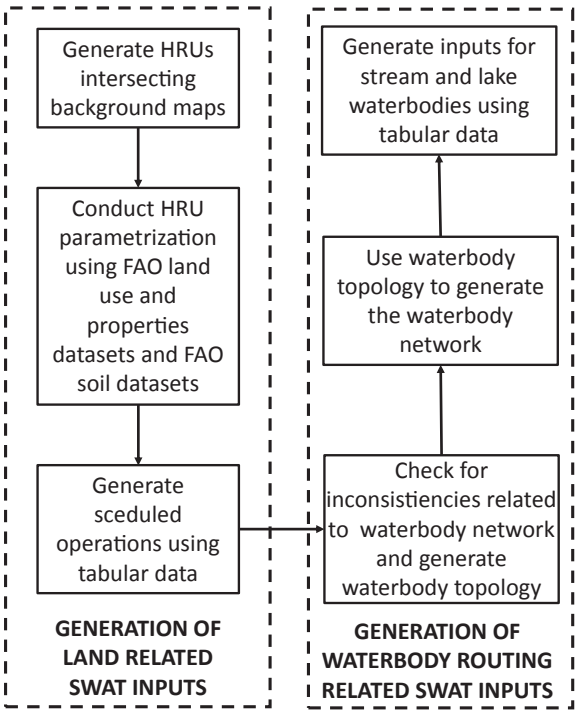
Generate HRUs intersecting background maps
Conduct HRU parametrization using FAO land use and properties datasets and FAO soil datasets
Generate sceduled operations using tabular data
GENERATION OF LAND RELATED SWAT INPUTS
Generate inputs for stream and lake waterbodies using tabular data
Use waterbody topology to generate the waterbody network
Check for inconsistiencies related to waterbody network and generate waterbody topology
GENERATION OF WATERBODY ROUTING RELATED SWAT INPUTS

**Fig. 1.** SWAT-LAB basic process sequence.

The described process might seem labour-heavy, and it was in the initial stage of the development. Hovewer, ArcGIS model-builder was used to automate the process of data pre- and post- processing. If a new region needs to be modeled, the modeler can re-use the same scripts to generate their imput quite fast, so the entire model setup process is semi-automated (the reader is referred to Appendix B for more details).

### 2.2. Case study description

To test this new SWAT model setup approach, a case study basin was chosen, which represents one of the developed sub-models. The catchment is situated mostly in Belarus and holds the upper basin of Neris River, which is a tributary to Nemunas River (Fig. 2). This river is called Neris in Lithuania, and Vilija in Belarus. The modeled catchment is situated largely in the Belarus; hence, we followed the local naming of the river.

The terrain of the Vilija River basin is an alternation of vast hills, plains and lowlands. Absolute heights range from 8 m to 385 m (Fig. 4b). The terrain has the major influence on soil erosion processes and, at the same time, is changing due to these processes. A great impact on the progress of erosion has the steepness and the length of the slopes. Prerequisites for notable soil erosion are established at the slopes of 2–3°, and areas with such slopes comprise about half of all agricultural lands of Belarus (Fig. 4c). About 50% of the country's arable land is located on the slopes, which are divided according to the steepness in the following way: from 1 to 3° – 38.6%, from 3.1 to 5° – 7%, from 5.1 to 7° – 1.2% and over 7° – 0.7% (Marchik (Марчик) and Jefremov (Ефремов), 2006).

The majority of landuse in the case study area (Fig. 4f) is classified as Cropland-Woodland mosaic (78.2%), followed by Cropland-dryland (16.96%), and the rest are forested areas and grasslands. There were no major cities in the region, only medium to low density settlements.

The soil distribution in the case study area is provided in Fig. 4d. Sod-podzolic soils predominate on the territory of the Belarus Republic (42.4%). They develop under the conditions of automorphic moistening, and are characterized by a low content of humus (up to 2%) and a weakly cloddy structure. Sod-podzolic marsh soils occupy 25.3% of the territory; this type develops under conditions of difficult flow, which contributes to stagnation of atmospheric precipitation on the surface of the soil. The soil is strongly leached, contain 1–3% humus. Peat bog soils occupy 14.2% of the territory. They are characterized by high potential fertility and, after drainage, they produce high yields of agricultural crops. Floodplain (alluvial) soils occupy about 9% of the territory, located in floodplains of river valleys, and are erosion-resistant, contain a significant amount of humus, have a strong, fine-lumpy structure and are used mainly under hayfields and pastures.

A major part of the study area are the waterbodies. The area holds a large reservoir, called the Vilejsko – Minsk water system, which stores and supplies water for the capital of Belarus – Minsk. The largest lake in Belarus – Lake Narach is also situated in the study area. Apart from large waterbodies, the area is densely covered in smaller and medium-sized lakes and reservoirs (Fig. 4).

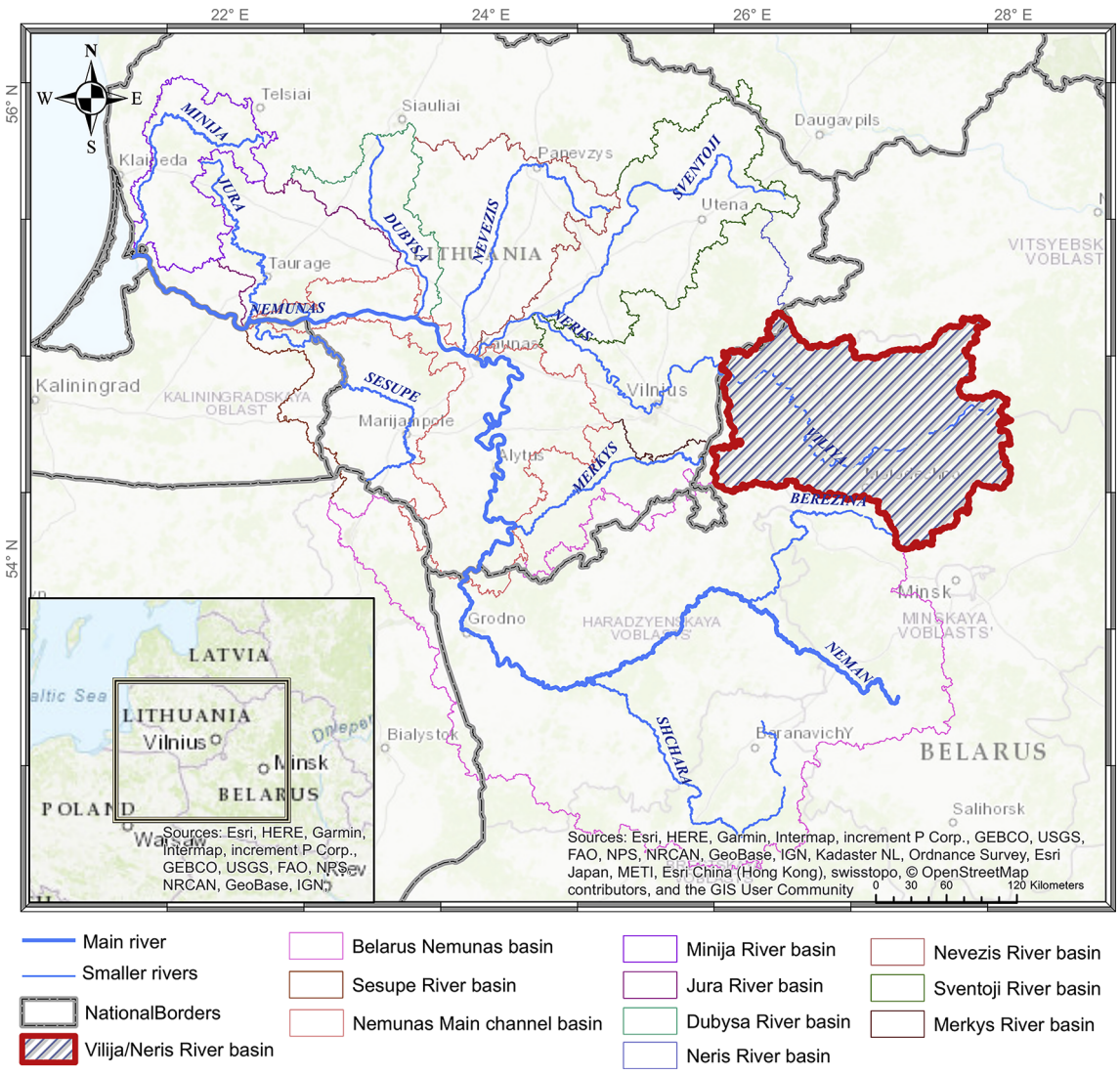


**Fig. 2.** Map of the Nemunas River Basin with sub-model division (Vilija basin is highlighted with a striped pattern).

**Table 2**
Data sources for the SWAT model setup and their original scale.

| Data layer | Lithuania | Belarus |
|---|---|---|
| DEM | National Land Service under the Ministry of Agriculture of Republic of Lithuania (digital spatial laser scanning points data of land surface of the Republic of Lithuania (National Land Service under the Ministry of Agriculture, 2009) | The Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global data was used for the DEM of the Republic of Belarus and Russian Federation Kaliningrad Oblast. ASTER GDEM is a product of NASA and METI (METI and NASA, 2009). |
| Original scale | 5 m × 5 m | 35 m × 35 m |
| Landuse | The National Reference Base Data Set (National Land Service under the Ministry of Agriculture, 2017). | WaterBase project database (International Institute for Software Technology and Institute for Water, 2010) |
| Original scale | 1:10 000 | 250 m × 250 m |
| Soil | National Land Service under the Ministry of Agriculture (National Land Service under the Ministry of Agriculture, 2001) | FAO (Nachtergaele et al., 2009) |
| Original scale | 1:10 000 | 1:5 000 000 |

**Table 3**
Average seasonal changes in temperature and precipitation in the territory of Belarus of two climate change scenarios (RCP4.5 and RCP8.5).

| Scenario | Temperature | | | | Precipitation | | | |
|---|---|---|---|---|---|---|---|---|
| | Winter | Spring | Summer | Autumn | Winter | Spring | Summer | Autumn |
| RCP4.5 | 2.4 | 2.1 | 1.6 | 1.7 | 9 | 1 | 1 | 8 |
| RCP8.5 | 3.1 | 2.6 | 2.3 | 2.5 | 10 | 4 | -3 | 4 |

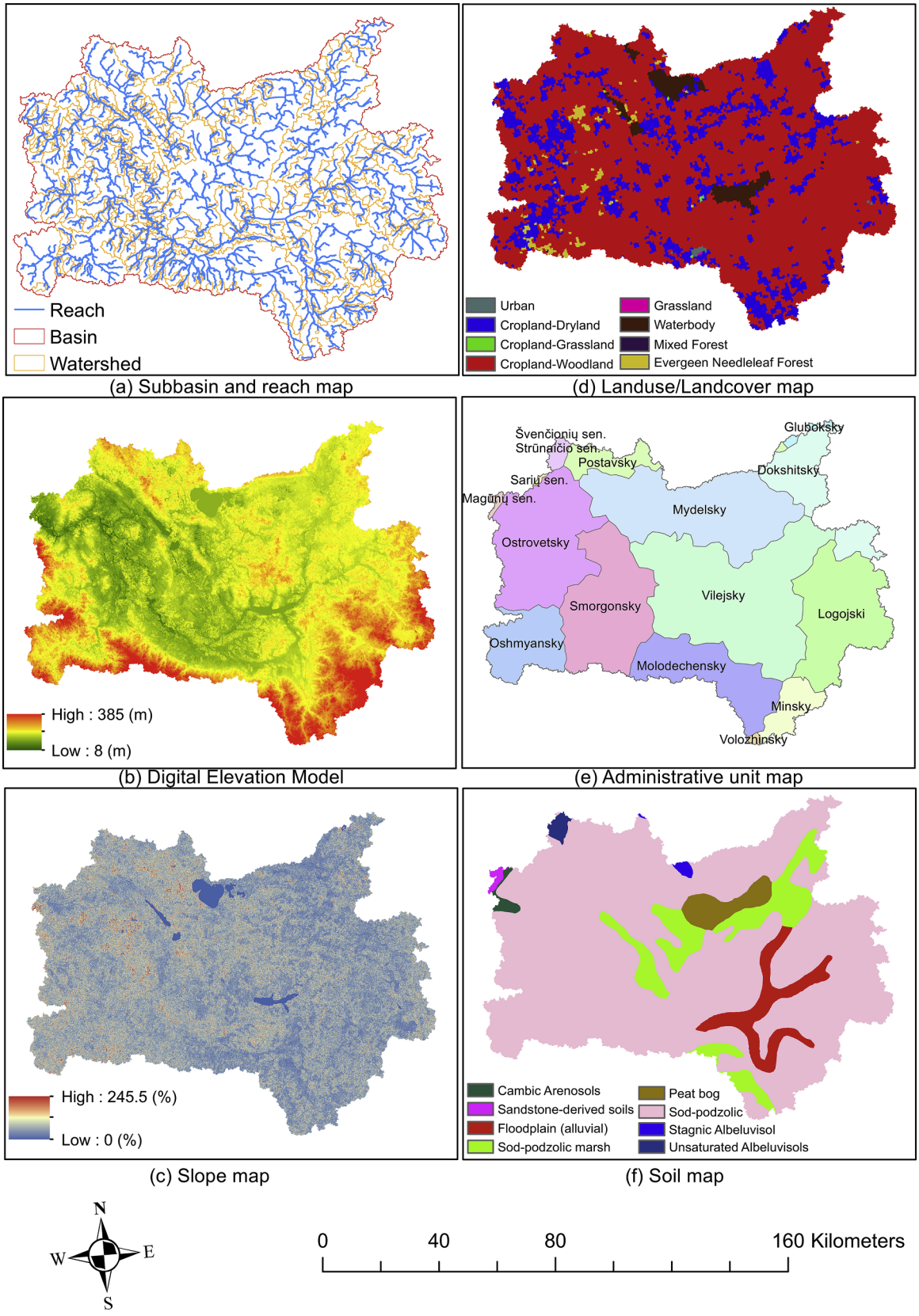


**Fig. 3.** Data layers for the SWAT model: a) stream network and subbasin grid; b) DEM; c) slope map; d) landuse map; e) administrative unit map; f) soil map (high resolution maps are available in the electronic supplement).

**Table 4**
Fitted parameter values in the calibration process.

| Parameter | Description and process | Fitted value |
|---|---|---|
| CANMX | Maximum canopy storage (mm $H_2O$). Affects infiltration, surface runoff and evapotranspiration | 25 |
| GW_DELAY | Groundwater delay time (days). Affects groundwater flow. | 120 |
| ALPHA_BF | Baseflow alpha factor (1/days). A direct index of groundwater flow response to changes in recharge. | 0.1 |
| GWQMN | Threshold depth of water in the shallow aquifer required for return flow to occur (mm $H_2O$) | 350 |
| SOL_AWC | Available water capacity of the soil layer (mm $H_2O$/mm soil). | *2 |
| SOL_K | Saturated hydraulic conductivity (mm/hr). | *8 |
| SMFMX | Melt factor for snow (mm $H_2O$/°C·day) | 7.5 |
| CMN | Rate factor for humus mineralization of active organic nutrients (N and P) | 0.001 |
| HLIFE_NGW | Half-life of nitrate in the shallow aquifer (days). | 10 |
| N_UPDIS | Nitrogen uptake distribution parameter | 15 |
| ERORGN | Organic N enrichment ratio for loading with sediment. | 1.3 |
| PPERCO | Phosphorus percolation coefficient (10 $m^3$/Mg) | 17.5 |
| ERORGP | Phosphorus enrichment ratio for loading with sediment | 1.3 |

* Stands for relative change.

**Table 5**
Overview performance statistics for the model calibration and validation.

| Parameter | Calibration | | | Validation | | |
|---|---|---|---|---|---|---|
| | $R^2$ | NS | PBIAS | $R^2$ | NS | PBIAS |
| Daily Flow | 0.66 | 0.66 | 4.49 | 0.67 | 0.66 | 3.53 |
| Monthly Flow | 0.80 | 0.83 | −6.09 | 0.79 | 0.76 | 2.03 |
| Sediment | 0.40 | 0.45 | −10.41 | 0.58 | 0.34 | −17.5 |
| TN | 0.71 | 0.61 | −0.54 | 0.53 | 0.56 | 10.83 |
| TP | 0.55 | 0.42 | −7.77 | 0.48 | 0.40 | 7.32 |

### 2.3. Data

The data gathering for a transboundary model is a difficult task in many aspects. In most cases, regional high-resolution and measurement data are gathered and stored by the Environmental protection agencies (EPA) and other governmental institutions. Even if the data is obtained, it has to be translated to the language of convenience and the measurement units have to be unified. For this study area, the data was obtained thru several governmental sources in different countries as well as public open access databases.

#### 2.3.1. DEM data

The DEM (Digital Elevation Model) was obtained thru different sources for different modeled regions (Table 2). All of the maps, including the DEM, were pre-processed in such manner:

- Combining the maps (where necessary);
- Re-projection of data to the appropriate UTM band;
- Cutting the maps to represent the study area with buffered areas;
- Resampling the maps to a unified 35 × 35 m grid;
- Snapping layers to uniform grid.

To automate this task the ArcGIS model builder was used to create custom procedures for a batch execution of sequential commands (see Appendix B for further details). These procedures may be re-used in further studies, as any user wishing to pre-process such datasets for model input can adopt them.

#### 2.3.2. Landuse data

As with the DEM data, similar problems were faced when creating the landuse database for the model input: the datasets had to be obtained from different sources, both public and regional authorities (Table 2); data had to be standardized between the regions; uncertainties in the data had to be handled with regards to location and the source. Further details are given in Appendix C.1.

#### 2.3.3. Soil data

Soil data had to undergo the similar procedures as the landuse dataset, but the main difference is the data source. Fortunately, a global-scale soil database is available from the FAO (Nachtergaele et al., 2009) and can be converted to SWAT classes (Gies and Merwade, 2014); this greatly reduces the data inhomogeneity and processing time. Nevertheless, a more accurate spatial data set of soil for the territory of the Republic of Lithuania at scale 1:10 000 was used (Table 2), provided by National Land Service under the Ministry of Agriculture (National Land Service under the Ministry of Agriculture, 2001). Further details are given in Appendix C.2.

#### 2.3.4. Other model input data

Other used datasets include: Administrative units, Fertilization practices and point sources, Crop yield, River network data, Reservoir and Lake/Pond data, Meteorological data, Flow and Water quality observation data. A detailed description of each dataset, pre-processing and the source is available in Appendix C.3-9.

#### 2.3.5. Climate change scenarios

Climate scenarios based on IPCC AR5 RCP4.5 and RCP8.5 (Collins et al., 2013) were defined for this study. The RCP4.5 is a stabilization scenario, where radiative forcing alleviates at 4.5 W $m^{-2}$ in the year 2100 without exceeding that value. The RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change, thus resulting in very high greenhouse gas emissions. Altered values for minimum and maximum daily temperature, humidity, solar radiation and precipitation data were forced, along with $CO_2$ concentration change, to produce runoff, sediment and nutrient response of the modeled area. Other modeled processes, such as management practices, reservoir operations, groundwater nutrient concentrations were not altered.

Analysis of calculations based on the moderate and likely scenario of climate change RCP4.5 shows a change in climate characteristics in the territory of Belarus by the end of the century. The projected mean annual temperature will increase by 2 °C by the end of the century, with a more significant increase in the winter-spring months. Projections indicate an increase for precipitation in the autumn and winter periods. In spring and summer it will not change much, but moisture supply in summer will decrease due to higher air temperature and transpiration by plants (Мельник et al., 2017).

Calculations of seasonal air temperature and precipitation for the more extreme scenario of global climate change RCP8.5 show that in this case, the heat supply for the vegetation period will increase even more, and in summer, due to high temperatures and lack of moisture, the aridity of the territory will increase (Мельник et al., 2017). A summary of the yearly average changes for different seasons are provided in Table 3.

## 3. Model calibration and validation

The finalized Vilija sub-model consists of 647 sub-basins (Fig. 3a), 1584 HRUs, and the total watershed area is 10 908.88 $km^2$. The model was calibrated and validated using a manual calibration approach, which was performed in accordance with the recommended procedure: 1) calibration of surface flow, followed by 2) calibration of baseflow, 3) sediment calibration and, final, 4) nutrient calibration for Total P and

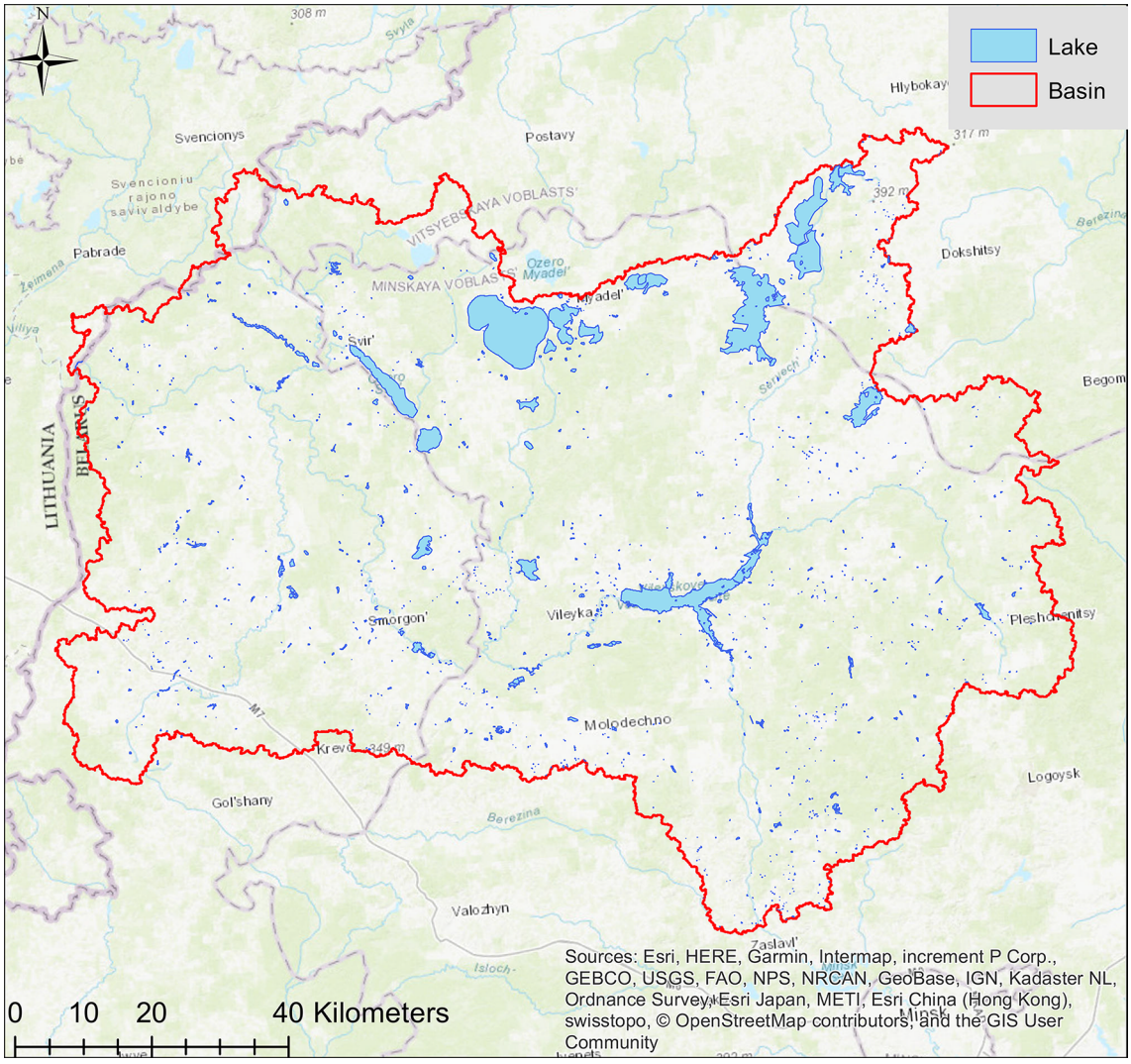


**Fig. 4.** Distribution of lakes in the Vilija river subbasin.

Total N. Although this study focuses only on the total nutrient loads, future model enhancement plans include separation of the loads to mineral and organic components, which SWAT is able to simulate. First, all the calibrated parameter values (except CN) were transferred from the previous SWAT modeling study in the area (Čerkasova et al., 2016) by altering the values of the previously calibrated parameters of the watershed area. Afterward, a manual calibration was performed by changing the process-associated parameter values. The parameters and fitted values are provided in the Table 4.

The resulted model using the SWAT-LAB setup did not require any changes to the most commonly used parameter for calibration, the Curve Number (CN). Other parameters were tested for their sensitivity, but none of them was sensitive enough to be of much influence to the model output.

To assess the model performance a set of statistical and graphical methods were chosen according to Moriasi (2015). The statistical performance measures are: coefficient of determination ($R^2$), Nash Sutcliffe efficiency (NS) and percent bias (PBIAS). Graphical performance measures are hydrographs, percent exceedance curves, scatterplots and box and whiskers diagrams for the measured and simulated outputs. According to Moriasi (2015), model performance can be judged as "good" for flow simulations if monthly NS and $R^2 > 0.7$; "satisfactory" for sediment if monthly NS $> 0.45$ and $R^2 > 0.4$. Model performance in simulating N/P is judged as "good" if $0.50 < NS \leq 0.65$, or "satisfactory" if $0.35 < NS \leq 0.50$, and $0.60 < R^2 \leq 0.70$ or $0.30 < R^2 \leq 0.6$ accordingly.

Judging by the achieved performance measures values provided in Table 5, the constructed model performance for flow, sediments and nutrients can be judged as "good" to "satisfactory" (Moriasi, 2015). A more detailed analysis of the calibration and validation is presented in the following sections of this paper.

### 3.1. Hydrology

The flow calibration and validation periods were 2000–2006 and 2007–2010. The calibration included both dry and wet years, as did the validation periods. Good model performance, according to Moriasi (2015), was achieved for monthly flow (R2 = 0.796, NS = 0.83 for the calibration and R2 = 0.792, NS = 0.76 for the validation period), and satisfactory for the daily flow (R2 = 0.66, NS = 0.697 for the calibration, and R2 = 0.67, NS = 0.43 for the validation period) simulations (Fig. 5).

The model shows a good measure of agreement for flow rates, with some underestimation of low flows and over estimation of mid-high flow rates (Fig. 6). We aimed at having a good measure of confidence on the daily basis for flow, as the observation data for water quality was scarcely available. We recognize, that the relationship between the water quality parameters and hydrology is not linear, nevertheless, a good daily river discharge representation provides a strong backbone for achieving satisfactory model performance in sediments and

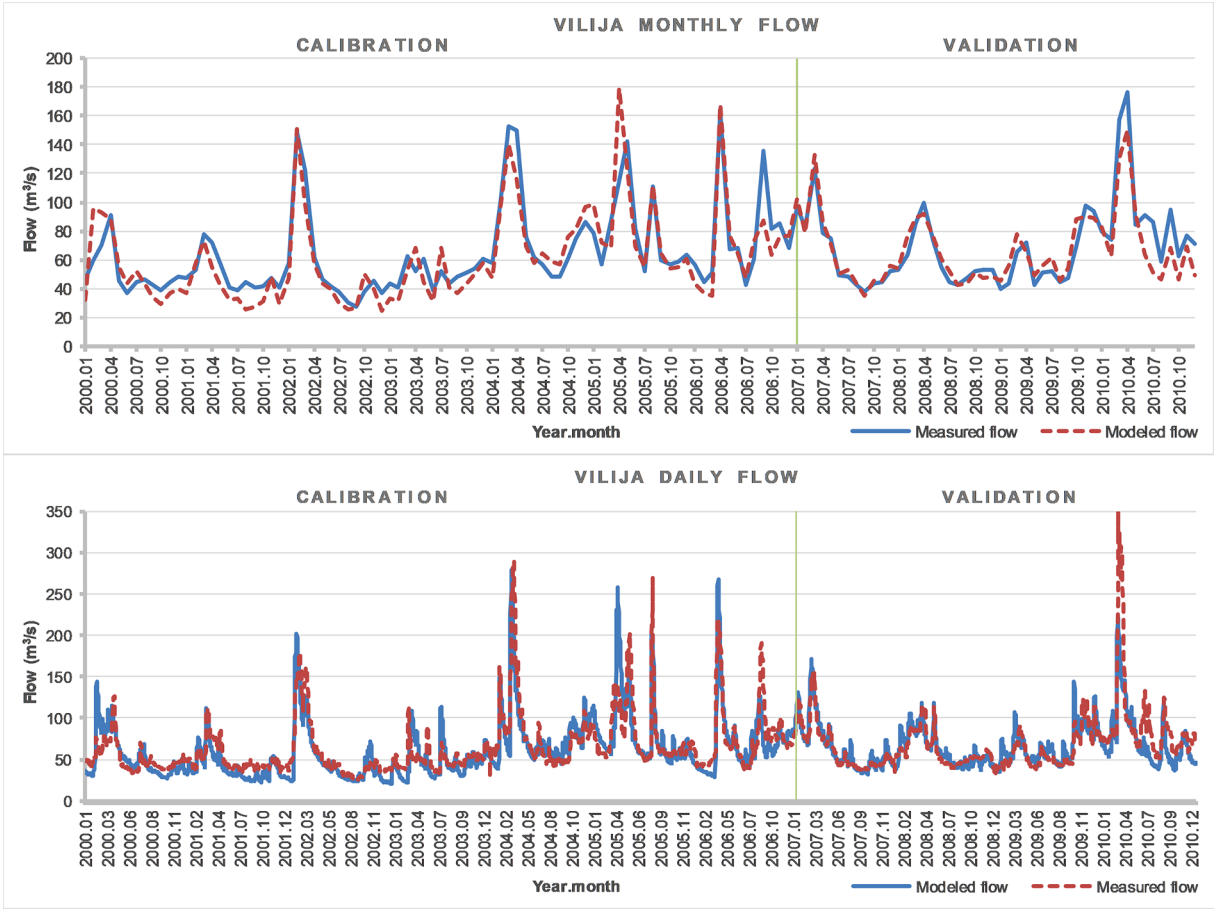


**Fig. 5.** Vilija River hydrographs for the average daily and monthly flow calibration and validation period.

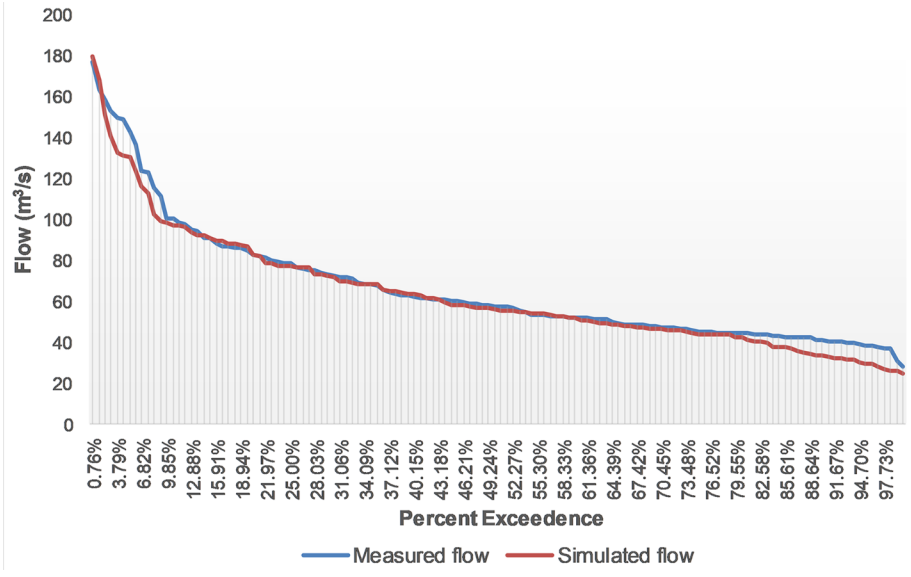


**Fig. 6.** Percent exceedance probability curves of observed and simulated monthly flows.

nutrients.

### 3.2. Sediments

Sediment calibration provided somewhat a challenge, as the only available observation data related to sediments was the Total Suspended Sediment (TSS). The measurements were performed by-weekly at the observation point close to the Lithuania-Belarus boarder. The observed value includes the measurements of solids as well as the organic compound of the sediments. Having no alternative, the sediment load was calibrated using the sediment concentration values of the model output. Studies conducted for large watershed sediment load assessments (Vigiak et al., 2017, 2015) acknowledge the challenges of sediment modeling, where data availability is limited and fragmented.

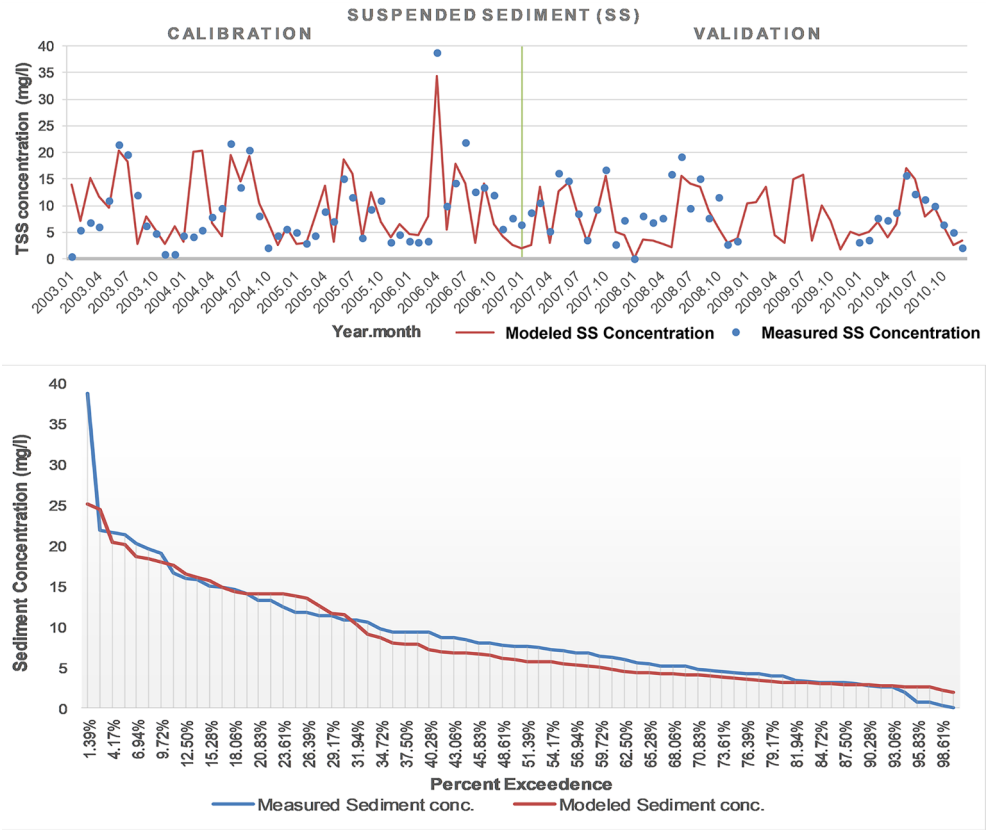


**Fig. 7.** Measured and simulated total suspended sediment concentration (top) and percent exceedance probability curves of observed and simulated monthly sediment concentration.

Keeping in mind that the available observational data has a high uncertainty attributed to it, the aim of the calibration was to reproduce the pattern of observations and achieve some measure of confidence on monthly basis, rather than focusing on forcing the model to seamlessly reproduce the observed values, which, given the complexity of the area and uncertainty in the setup and observed data, would be next to impossible.

The observed data for TSS was available for limited amount of years and with gaps, so the period was divided into 2003–2006 for calibration, and 2006–2010 for validation, excluding the year 2009 for lack of data. Satisfactory model performance was achieved for sediment concentration in both calibration (R2 = 0.4, NS = 0.44) and validation (R2 = 0.58, NS = 0.34) periods.

The percent exceedance probability curves of observed and simulated monthly sediment concentrations show an adequate agreement (Fig. 7), with one outlier exception at the maximum concentration value, which in turn might have been an error in the observation. Considering that the modeled runoff performance was satisfactory for monthly and daily flow rates, the modeled sediment loadings should be in par with observed loadings, although there are no adequate measurement data to confirm this hypothesis.

### 3.3. Nutrients

The amount of nutrients transported by the Vilija River from Belarus to Lithuania was and is monitored by conducting by-weekly measurements at the station near the Lithuania-Belarus boarder. The available data for both TN and TP was for 8 years (2003–2010), so the period was split into 2003–2007 for calibration, and 2008–2010 for validation. The inconsistency in the selection of periods for flow and water quality calibration and validation periods was because the selection was optimized with respect to the availability of the measurement data.

#### 3.3.1. TP

As the modeled phosphorous concentration in the river depends on the sediment regime, there were no major difficulties with the calibration of TP, because sediment concentration was calibrated prior to nutrients. Nonetheless, at first the model constantly under-predicted the phosphorous concentration. This problem was solved by considering the groundwater contribution of phosphorus. The SWAT does not directly model the phosphorous pool in the shallow aquifer (Neitsch et al., 2011), however a concentration of soluble phosphorous in the shallow aquifer and groundwater flow can be specified to account for loadings of P with groundwater. An analysis of literature (Ministry of natural resources and environmental protection of the Republic of Belarus, 2015, 2014, 2009) stated that phosphorous concentration is present and measured in the groundwaters of Belarus through multiple years. The concentration varies over the seasons, ranging from 0.01 to 0.1 mg/l. This feature of the groundwater in the case study area and the P modeling approach used by SWAT can explain the constant TP underprediction. The model setup was altered, and a groundwater P loading was added based on values provided in the literature. This alteration helped achieve satisfactory results for TP for the calibration and validation periods (Fig. 8)

#### 3.3.2. TN

The Total Nitrogen calibration was conducted using the standard procedure of calibrating the parameters attributed to mineral N and organic N loadings, followed by in-stream water quality processes. Organics are transported to the stream attached to sediment, so the movement of sediment had the major influence on organic N concentration and followed the same pattern as the sediment loadings. The mineral N loading is attributed to fertilization practice, which was setup in the management files according to the Ministry of Agriculture and Food of the Republic of Belarus technological scheme for application of

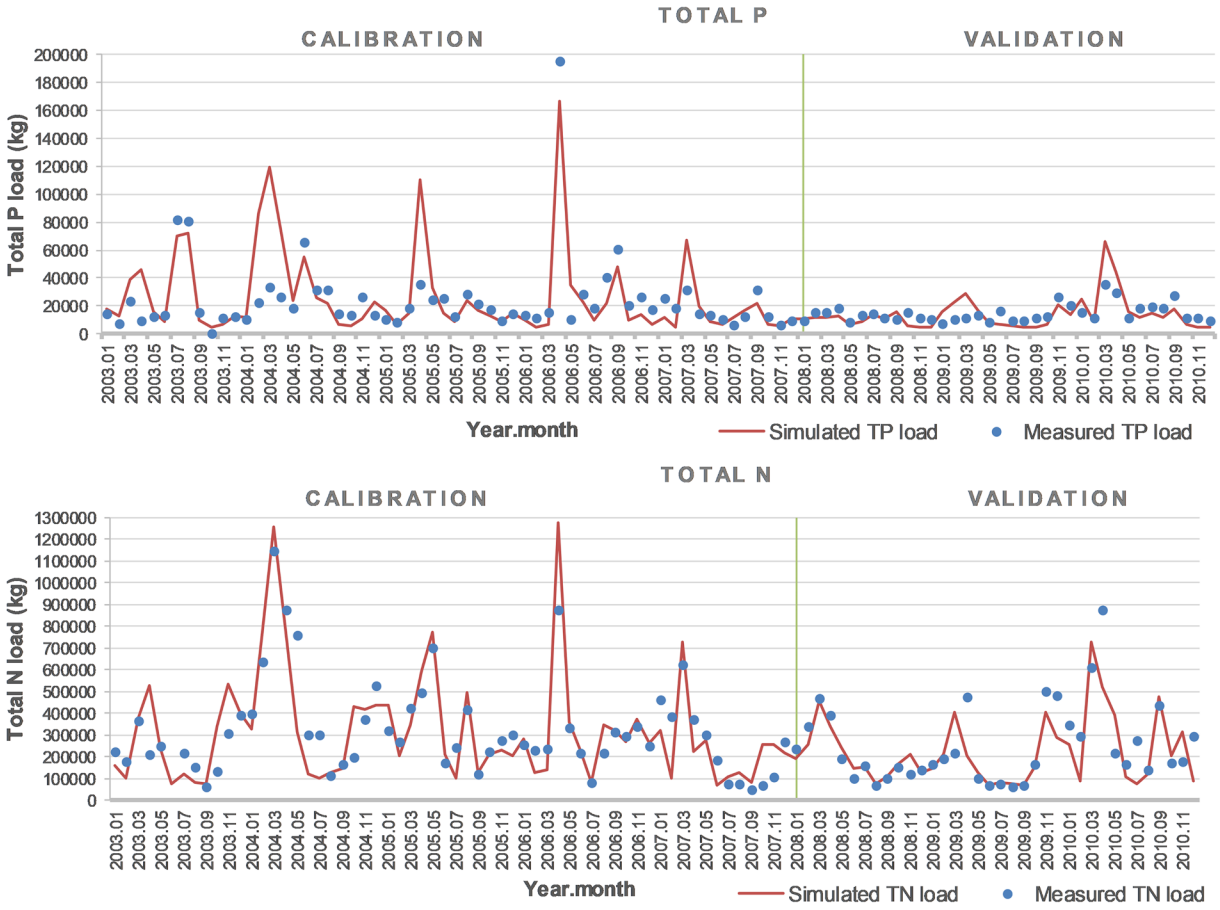


**Fig. 8.** Total Phosphorus load (top) and Total Nitrogen load (bottom) to the Vilija river for calibration and validation periods.

**Table 6**
Model performance statistics for each month and attributed nutrient loads.

| Month | Modeled daily flow statistics | | | | Total N load | | | Total P load | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $R^2$ | NS | PBIAS | Percent of the yearly flow (%) | Average TN load (kg) | Monthly TN load (kg) | Percent of the yearly load (%) | Average TP load (kg) | Monthly TP load (kg) | Percent of the yearly load (%) |
| Jan | 0.75 | 0.46 | 4.95 | 7.64 | 300217 | 2401735 | 8.58 | 13673 | 109384 | 5.35 |
| Feb | 0.69 | 0.6 | −4.01 | 8.87 | 317487 | 2539892 | 9.07 | 13608 | 108865 | 5.33 |
| Mar | 0.59 | 0.65 | 6.16 | 12.10 | 511867 | 4094937 | 14.63 | 23736 | 189890 | 9.29 |
| Apr | 0.41 | 0.46 | 2.24 | 13.05 | 571737 | 4573892 | 16.34 | 43460 | 347682 | 17.01 |
| May | 0.61 | 0.69 | 3.50 | 9.07 | 357538 | 2860302 | 10.22 | 13933 | 111463 | 5.45 |
| Jun | 0.36 | 0.55 | 3.50 | 6.74 | 173461 | 1214227 | 4.34 | 24550 | 196396 | 9.61 |
| Jul | −0.12 | −0.07 | −2.65 | 6.97 | 179867 | 1438925 | 5.14 | 24619 | 196955 | 9.64 |
| Aug | 0.83 | 0.8 | 2.50 | 6.83 | 156624 | 1252992 | 4.48 | 29435 | 235483 | 11.52 |
| Sep | 0.48 | 0.55 | 15.07 | 6.33 | 165744 | 1325955 | 4.74 | 24602 | 196819 | 9.63 |
| Oct | 0.52 | 0.07 | 2.20 | 7.10 | 177226 | 1417805 | 5.07 | 13434 | 107475 | 5.26 |
| Nov | 0.82 | 0.78 | 5.68 | 7.60 | 276236 | 2209888 | 7.89 | 16719 | 133751 | 6.54 |
| Dec | 0.75 | 0.56 | 6.60 | 7.69 | 332664 | 2661312 | 9.51 | 13738 | 109902 | 5.38 |

fertilizers.

As in the case of TP, TN loadings were underestimated during months, when groundwater flow was predominant. Literature analysis provided the observed amount of nitrogen in the groundwater of the area (Ministry of natural resources and environmental protection of the Republic of Belarus, 2014). With SWAT2012 the nitrate pool in the shallow aquifer is modeled, allowing for fluctuations in nitrate loadings in the groundwater over time (Neitsch et al., 2011). A key calibration parameter for nitrogen concentration in the shallow aquifer was the half-life (HLIFE_NG). This parameter accounts for losses of nitrate due to biological and chemical processes in the shallow aquifer, and describes a net effect of all reactions occurring in the aquifer. After performing the described parameter value alternations, satisfactory model performance was achieved (Fig. 8) for calibration and validation periods.

### 3.4. Inter-seasonal performance

To correctly identify seasonal performance of the model, performance statistics were calculated for each month, providing the insight of possible unsatisfactory model predictions. As the summary shows (Table 6), only one month, July, failed to produce reliable statistics, based on $R^2$ and NS. Usually, this is the driest month of the year and produces low flows. This tendency is also demonstrated in the flow

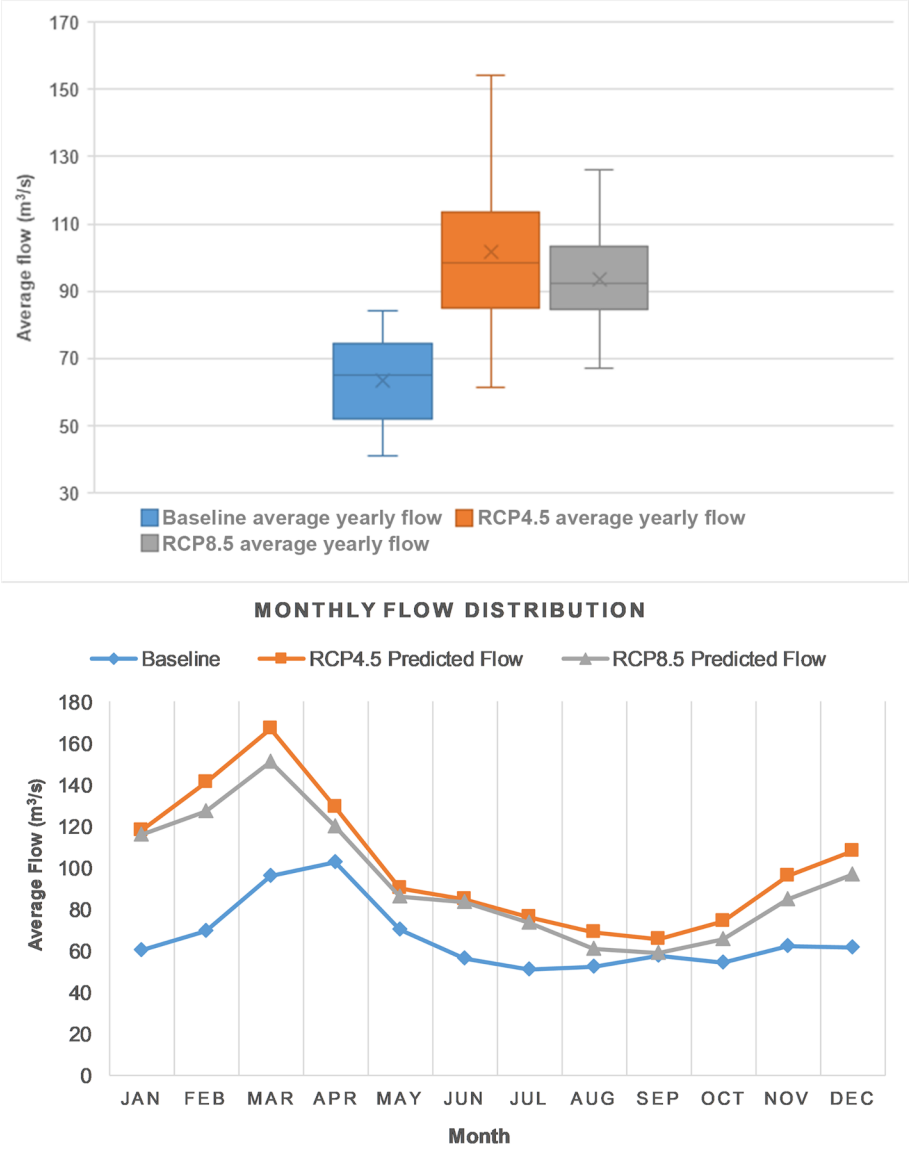


**Fig. 9.** Yearly flow rate change (top) and average monthly flow distribution change (bottom) under two climate change scenarios (RCP4.5 and RCP8.5).

percent exceedance probability curve (Fig. 6), where model is clearly under-predicting low flows.

On the other hand, on average, only 5.14% of the total yearly N load and 6.94% of the total yearly P load is delivered downstream during July. Nevertheless, when performing intersessional future climate change assessment, one has to make sure that the model is well calibrated on yearly, monthly or daily time step, as well as in individual months. Such assessment provides basis for discussion, whether the model is adequately representing the foreseen changes.

## 4. Climate change effects

With the model setup and parametrization complete, we could simulate the change in the hydrology and water quality of the Vilija River. The most important task was to assess the possible changes of the nutrient loadings to the Lithuanian rivers (Neris and Nemunas) from Belarus under possible climate change scenarios. The outcome of this study will be used to assess possible nutrient reduction measures, which could be used to reach the set targets of N and P loading ceilings for Lithuania, defined by the Nutrient Reduction Scheme of HELCOM (HELCOM Ministerial Meeting, 2007).

### 4.1. Hydrology

On average, it is expected for the yearly discharge to increase by 47.6%, with a more significant increase simulated in the RCP4.5 – 53.7% (Fig. 9 top). This outcome is somewhat expected, as the total annual precipitation should increase (Table 3). In the RCP8.5 the increase in the average yearly flow is less significant – 41.6%, due to the fact that less precipitation is expected in the summer months by the end of the century (Table 3).

As with many forecasts in the similar regions (Čerkasova et al., 2016; Denisov (Денисов), 2017; Kriaučiunienė et al., 2008; Stonevičius et al., 2017) it is expected that the so-called “flood season” will shift from spring months (March-April), to late winter, early spring (February-March) (Fig. 9 bottom). With the rise of temperature in winter season, snow cover will form rarely and is expected to last less days. By the end of the century, the winter, as is expected to occur in the current form, will disappear from the majority of the Belarus territory (Мельник et al., 2017), with almost no snow cover predicted. Although, the Vilija River basin is situated in the northen part of Belarus, so theese changes might be more mild in the area. The hydrology is expected to change in the same manner, following the precipitation changes of the region.

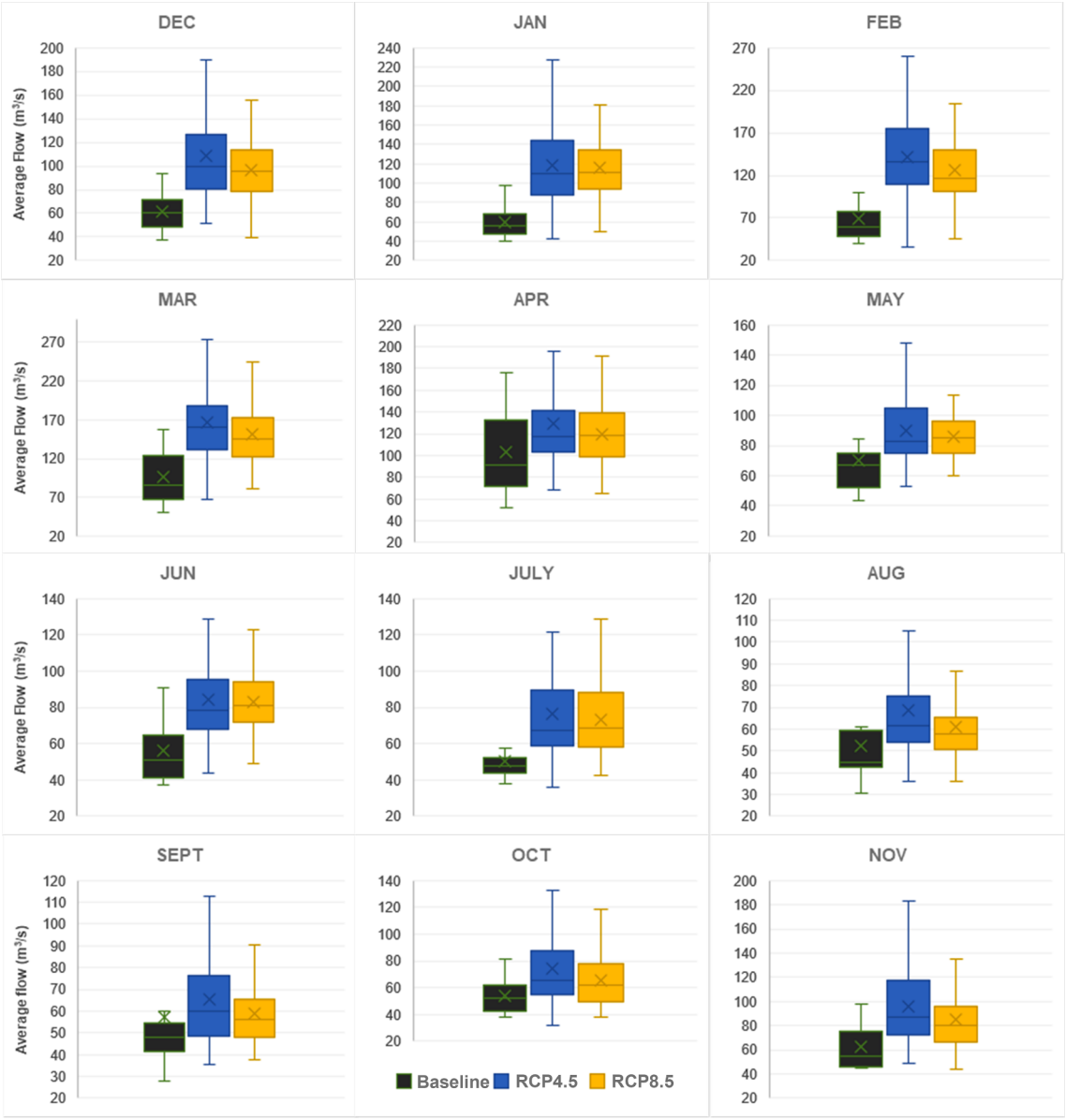


**Fig. 10.** Vilija River monthly change prediction statistics for the forecast period under two climate change scenarios (RCP4.5 and RCP8.5).

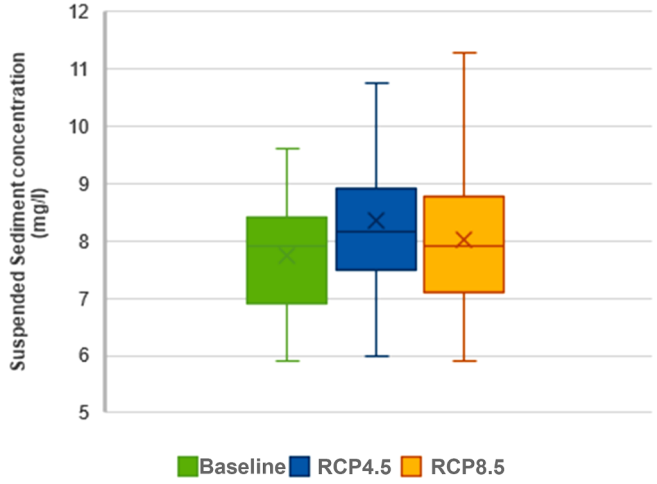


**Fig. 11.** Yearly average sediment concentration in the baseline period and under RCP4.5 and RCP8.5 scenarios.

Based on the model inter-seasonal performance (Table 6) the less reliable assumptions for the future change are produced in the July month, where, despite the projected precipitation reduction (in RCP8.5), there is a significant increase in discharge simulated (Fig. 10). However, a broader analysis should be conducted, separating surface runoff and baseflow, which might provide further information on the projected changes in the total flow composition.

April, September and October are the months with less prominent effects, where the median flow will experience no significant change and the mean flow if expected to increase on average of 19%, whereas winter months and November experience the highest increase in mean (up to two-fold increase) and median flows (Fig. 10).

### 4.2. Sediments

The projected yearly average sediment concentration does not experience any major changes (Fig. 11), in fact, the median concentration is ~8 mg/l during the baseline period and in the RCPs.

The projected changes in the concentration through the year varies slightly, with a larger concentrations modeled during summer months

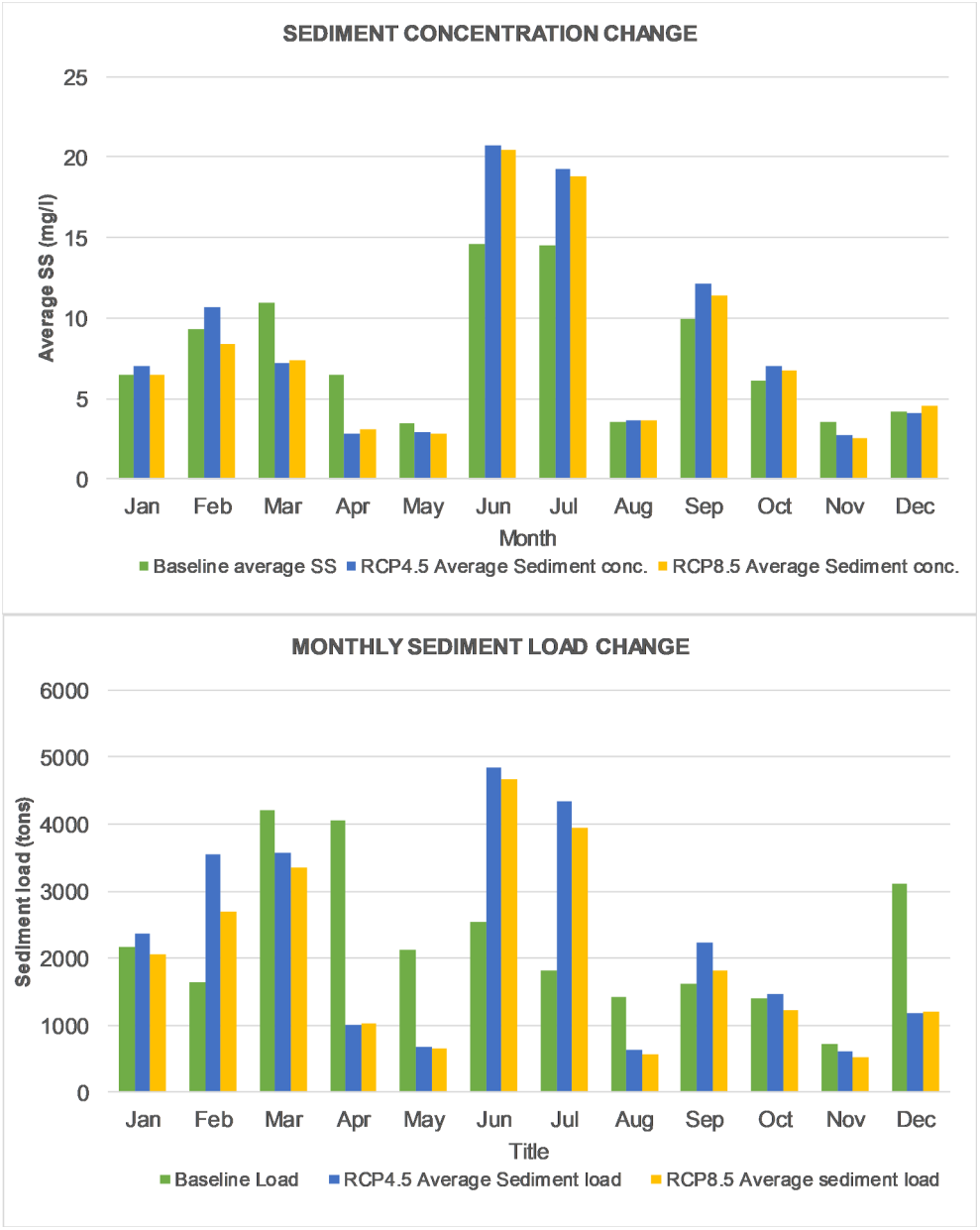


**Fig. 12.** Sediment concentration change (top graphs) and the average total sediment load to the Vilija River for the forecast period under the climate change scenarios (RCP4.5 and RCP8.5).

of June and July. A reduction in the SS concentration is modeled in May and April, whereas no substantial change is predicted in other months (Fig. 12 top).

The projected average total sediment load provides a slightly different picture, where there is a substantial reduction in sediment delivery in the April, May and December months, and a substantial increase in February, June and July months, especially in the RCP4.5 scenario (Fig. 12 bottom).

As the sediment data and calibration performance was the weakest point of this model, we have to treat these results with skepticism. A substantial change is modeled during July, which also displayed unsatisfactory performance during flow calibration, therefore it is expected that the projected change might be overestimated or underestimated for this month.

### 4.3. Nutrients

Total yearly nitrogen load is expected to increase under both RCP4.5 (by 27%) and RCP8.5 (by 16%) scenarios, and a more substantail increase expected in the RCP4.5 scenario. The mean and median loads will increase as well, whereas the minimum loads will not experience significant change (Fig. 13 top).

The monthly load distribution is subject to increase, espetially in periods from January to March and from September to November. A decrease in TN load is expected during the period from April to June. No substantial change is modeled in July, August and December (Fig. 13 bottom).

As for TP loads, the model indicates a decrease (on average of 10%) in the modeled yearly TP load, especially in the RCP8.5 scenario

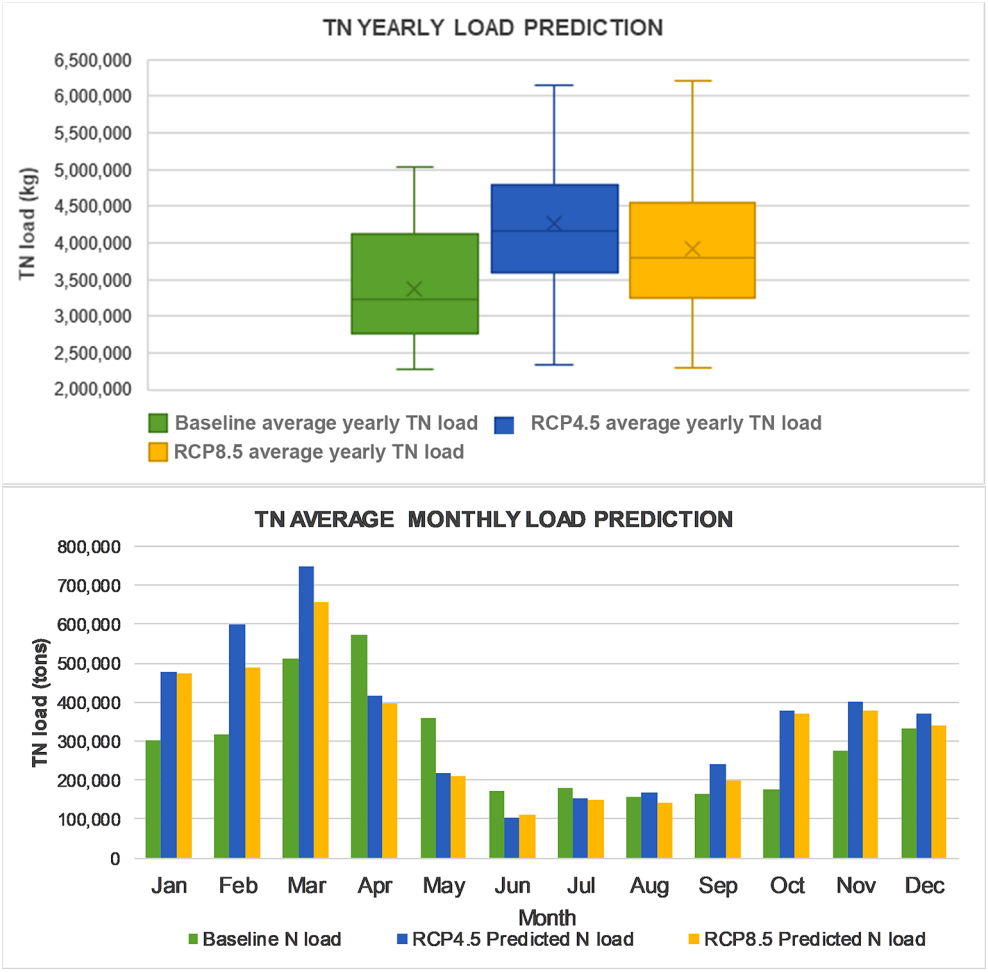


**Fig. 13.** Yearly Total N load (top) and Intersessional TN change (bottom) in the baseline period and under RCP4.5 and RCP8.5.

(16.14%). The mean TP load will not change much between the baseline and RCP4.5, but decrease under the RCP8.5 conditions (Fig. 14 top). The minimum TP load will not change in the RCP4.5; however, a 22% decrease in minimal loads is modeled in the RCP8.5.

Inter-seasonal TP loads will experience substantial changes, with a large increase (more than 2.5-fold) in the period from January to March, and a substantial decrease (by 70%) from June to November (Fig. 14 bottom). A more significant increase during winter and early spring is modeled in the RCP4.5 scenario, whereas the same changes seem to be milder under the conditions of the RCP8.5 scenario.

## 5. Discussion

### 5.1. Data, method and model setup

This study focuses on designing and assessing the practicability of an alternative SWAT setup method with enhanced HRU definition procedure for creating a high-resolution large-scale transboundary hydrological and water quality model, where data availability is limited and fragmented. Majority of data needed for model setup was attained thru public or open-assess sources (DEM, soil and landuse maps, fertilization practices), or was produced by using digitization methods (stream network and lakes/ponds/reservoirs). Though the data was fragmented and scattered, it was still possible to acquire and preprocess a substantial amount of it, or make use of studies in the region to approximate some parameter values, like the carbon content of the soil profile or the groundwater quality parameters. This study demonstrates that data scarcity becomes less of an issue in modern days, where the availability of public resources becomes better and the amount of stored and accessible information larger. This aspect is especially important when dealing with transboundary modelling studies, as it is a common case that data is not shared between countries, even if the issues related to water quality of the region are the same for every riparian country. The only difficulty might be the language barrier, although in the case of post-soviet union countries, some data might be available in Russian and a substantial part of the population have a certain degree of understanding of this language.

We successfully applied the SWAT-LAB for a case study site in one of the Nemunas River sub-watersheds – Vilija River basin, which is, for the large part, situated in Belarus. The model was calibrated using daily and monthly flow measurements from the observation point on the border between Belarus and Lithuania, and by-weekly TSS, TN and TP measurement data from the same point. Judging from the modeled area and performance statistics (Table 5 and Table 6), the model performance for the flow, sediments and nutrients can be judged as good to satisfactory (based on Moriasi, 2015). One aspect of model performance is the uncertainty causes. One has to keep in mind the vast diversity of data sources that were used in this study. It is doubtful that the measurement techniques are the same among the watershed countries. It is also noteworthy that there might be translation error when translating certain fields within the databases originating from different countries. All the data have to undergo a manual quality control to ensure that there are no outliers or systematic errors. Nevertheless, some uncertainty originates from the data itself and this has to be properly quantified in the model results.

Overall, the applied method displayed robustness and stability when

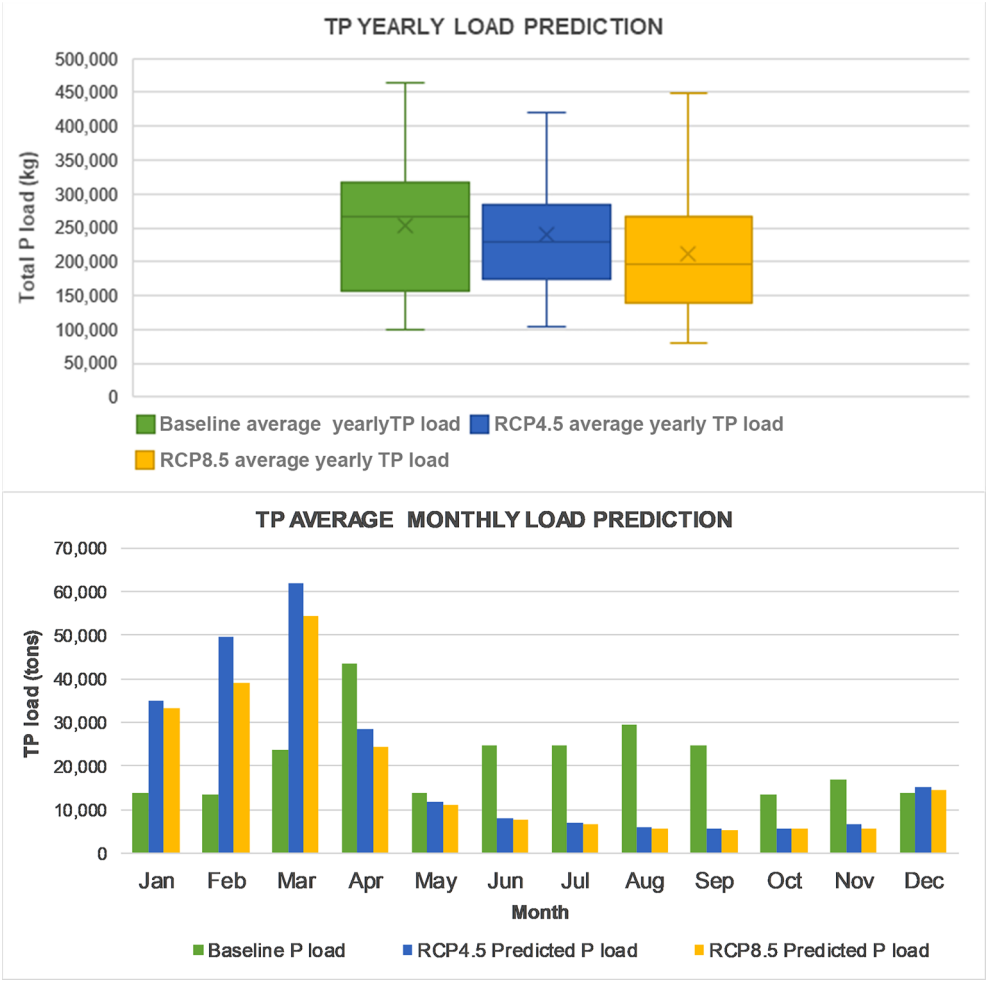


**Fig. 14.** Yearly Total P load (top) and Intersessional TP change (bottom) in the baseline period and under RCP4.5 and RCP8.5.

dealing with large-scale high-resolution model setup. We experienced no major difficulties running SWAT after the SWAT-LAB script-based model setup procedure. The model was calibrated using the same scripts as in the setup, so the user has the ability to change all the parameter values to their liking. One drawback, however, is that the modeler has to have some experience in both programming and/or scripting and hydrology and water quality at the same time. A certain understanding and knowledge of the area will not go amiss when setting up the SWAT-LAB model. Where minimum experience or understanding is required in the semi-automated and GUI based model setup programs, they lack the robustness and the flexibility of parametrization but are excellent tools for smaller and larger applications and studies, as proven by many publications in the SWAT database ("SWAT Literature Database for Peer-Reviewed Journal Articles," 2018).

As a useful byproduct of this study, a very detailed Nemunas River basin (along with its subbasins, including Vilija) stream network was produced by manual digitization. This data will be used in future studies in the region. Many ArcGIS models were constructed to automate the input data map preprocessing (like cutting the maps to a desired region, synchronizing the grids, etc.), therefore, after documentation, they can be released in open-access for use in similar studies. Currently, the reader can refer to the Appendices A and B for more details on the SWAT-LAB method and ArcGIS models. We invite those who are interested in using the created codes, models and/or data to contact us via the corresponding author for further details and instructions.

### 5.2. Climate change effects

Despite the RCP8.5 scenario being extreme of the projected changes, it appears that the effects of the RCP4.5 will result in drastic changes for the Vilija River hydrologic regime (Fig. 9). This relates to the projected changes in precipitation, as the amount of precipitation is likely to increase more in the RCP4.5 than in the RCP8.5. Nonetheless, the results reflect the mean changes, where the effects of summer droughts, high peak discharges related to storms and other extremes are overshadowed by averaging. For sure, the climate change will have a significant impact on the growing season of the crops, fertilization practice change and human activity, resulting in the possible increase of nutrient load to the rivers, if no mitigation measures will be undertaken.

This study confirms conclusions, derived from similar assessments (Denisov (Денисов), 2017), that a shift in seasons will likely happen due to projected changes. The spring flood season will shift to late winter; the crop-planting period will also be shifted to earlier dates. With the change in fertilization period, the nutrient loads will also change.

An interesting case is modeled for the summer months, especially July, where a significant increase in runoff is formed (Fig. 10). It is no surprise for the RCP4.5, where an increase in precipitation is projected, but should have been a different case in the RCP8.5, where a decrease in precipitation in summer months is foreseen. Some explanation could be provided by the distribution of surface and groundwater flow in the

modeled area. The majority of the flow is being generated by the lateral and groundwater flow, with little surface runoff contribution. Because the movement in the shallow aquifer usually has a specific lag attributed to it (when the water is being stored in the soil for some time), this process might play a role in the increase in discharge, despite receiving less precipitation.

Unexpectedly, the amount of TP load is projected to decrease, under both the RCP4.5 and RCP8.5 scenarios (Fig. 14). The minimum and the average loads appear to not change by much in the RCP4.5, nonetheless the total yearly load decrease is modeled. Inter-seasonal load change provide an interesting picture, where a significant increase in winter and March is modeled, following by a decrease in loads for the rest of the year (Fig. 14). The resulting increase in TP load in the winter follows the projected change in the flow distribution. However, in warmer months and the start of the growing season the graph changes. For sure, the earlier vegetation and crop-planting season will have an influence on the phosphorus uptake; though, a more prominent change is due to groundwater contributions. Contribution of surface runoff to the stream is less in warmer months, than the contribution of groundwater. Because phosphorus in the groundwater is not directly modeled in SWAT, we might underestimate these values. Nonetheless, if the system will experience a decrease in the phosphorus loads, it will have an impact downstream, especially to the Curonian lagoon. As the phosphorus is the limiting nutrient for the lagoon (Ertürk, 2008), we might observe less blooms. This is an interesting finding, although it might be misleading. A better phosphorus in the groundwater model is needed (potentially setup using the SWAT-MODFLOW (Park and Bailey, 2017)), which should provide improved approximations of TP loads in the light of changing climate.

An overall increase in the modeled Nitrogen load is being modeled, for both the RCP4.5 and RCP8.5, with a more significant change in RCP4.5 (Fig. 13 top). The inter-seasonal distribution of Nitrogen load is altered following the hydrology changes and the shifts in crop planting season start, projecting higher loads in late winter and March, and a significant decrease in April (Fig. 13 bottom). The TN load during summer and early autumn do not display any significant change, whereas October and November will receive a substantial increase in Nitrogen load. This is an outcome of both increased runoff and more plant residue available after they go dormant. This should be a big warning sign for the possible mitigation measures of nutrient reduction. When assessing the suitability or practicability of some of the measures, one should account for the possible changes in the nutrient load redistribution within the year. These results are a strong foundation for the planed future research direction for this model and the case study area.

### 5.3. Future work

Plans include the documentation of the SWAT-LAB code and making it available in open-access. As for the model, it will be used for a number of different studies of the area; all related to nutrient reduction measures for the Nemunas River basin. We are hoping to acquire more data within the scope of possible future projects in collaboration with Belarus partners; therefore, the model might undergo some improvements.

## Acknowledgments

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## Appendices A, B, and C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2018.09.025.

## References

ArcSWAT|Soil and Water Assessment Tool [WWW Document], 2012. URL https://swat.tamu.edu/software/arcswat/ (accessed 5.11.18).
Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B., Neitsch, S.L., 2012. Soil and Water Assessment Tool "SWAT" Input/Output Documentation, Encyclopedia of GIS. Texas. doi: 10.1007/978-0-387-35973-1_1231.
Baltic Marine Environment Protection Commission, 2018. Declaration of the Ministers of the Environment of the Baltic Coastal Countries and the EU Environment Commissioner, HELCOM Brussels Declaration 2018. Brussels.
Bartnicki, J., Benedictow, A., 2017. EMEP/MSC-W report for HELCOM Contributions of emissions from different countries and sectors to atmospheric nitrogen input to the Baltic Sea basin and its sub-basins.
Čerkasova, N., Ertürk, A., Zemlys, P., Denisov, V., Umgiesser, G., 2016. Curonian Lagoon drainage basin modelling and assessment of climate change impact. Oceanologia 58, 90–102. https://doi.org/10.1016/j.oceano.2016.01.003.
Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J., Wehner, M., 2013. Long-term Climate Change: Projections, Commitments and Irreversibility. Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang. 1029–1136. doi: 10.1017/CBO9781107415324.024.
Danile, F., 2013. Simplifying Watershed Modeling 133.
Denisov (Денисов), N. (H.), 2017. Adaptation strategy for Belarus agriculture.
Dile, Y., Srinivasan, R., George, C., 2017. QGIS Interface for SWAT (QSWAT) February, 77. doi: 10.13140/RG.2.1.1060.7201.
Dile, Y.T., Daggupati, P., George, C., Srinivasan, R., Arnold, J., 2016. Introducing a new open source GIS user interface for the SWAT model. Environ. Model. Softw. 85, 129–138. https://doi.org/10.1016/j.envsoft.2016.08.004.
Ertürk, A., 2008. Modelling the Response of an Estuarine Lagoon to Nutrient Inputs. Klaipeda University.
George, C., Leon, L.F., 2008. WaterBase: SWAT in an open source GIS. Open Hydrol. J. 2, 1–6. https://doi.org/10.2174/1874378100802010001.
Gies, L., Merwade, V., 2014. Creating SWAT Soil Database using FAO Soil and Terrain Database of East Africa (SOTER) Data.
HELCOM Ministerial Meeting, 2007. HELCOM Baltic Sea Action Plan. Krakow.
International Institute for Software Technology and Institute for Water, E. and H., 2010. WaterBase Project [WWW Document]. URL http://www.waterbase.org/download_data.html (accessed 1.25.16).
Kriaučiunienė, J., Meilutyte-Barauskiene, D., Rimkus, E., Kažys, J., Vincevičius, A., 2008. Climate change impact on hydrological processes in Lithuanian Nemunas river basin. Baltica 21, 51–61.
Marchik (Марчик), T.П. (T.P.), Jefremov (Ефремов), A.Л. (A.L.), 2006. Factors of soil formation and soils of the Republic of Belarus (ФАКТОРЫ ПОЧВООБРАЗОВАНИЯ И ПОЧВЫ РЕСПУБЛИКИ БЕЛАРУСЬ). In: Shtukin (Штукин), C.C. (S.S.), Sozinov (Созинов), O.B. (O.V.) (Eds.), Soil Science with the Basics of Plant Growing (Почвоведение с Основами Растениеводства). Grodno.
METI, NASA, 2009. ASTER global digital elevation model, U.S. Department of the Interior|U.S. Geological Survey. doi: 10.5067/ASTER/ASTGTM.002.
Ministry of natural resources and environmental protection of the Republic of Belarus, 2015. National environmental monitoring system of the Republic of Belarus: results of observations (Национальная система мониторинга окружающей среды Республики Беларусь: результаты наблюдений). Minsk.
Ministry of natural resources and environmental protection of the Republic of Belarus, 2014. Groundwater monitoring (Мониторинг подземных вод), in: Klebanovich (Клебанович), H.B. (N.B.), Apanasevich (Апанасевич), S.V. (C.B.) (Eds.), National Environmental Monitoring System of the Republic of Belarus: Results of Observations. РУП «Бел НИЦ «Экология», Minsk, pp. 93–134.
Ministry of natural resources and environmental protection of the Republic of Belarus, 2009. Природные воды (Natural Waters). Ministry of natural resources and environmental protection of the Republic of Belarus, pp. 115–188.
Moriasi, D., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. Trans. ASABE 58, 1763–1785. https://doi.org/10.13031/trans.58.10715.
MWSWAT|Soil and Water Assessment Tool [WWW Document], 2012. URL https://swat.tamu.edu/software/mwswat/ (accessed 5.11.18).
Nachtergaele, F., Velthuizen, H. Van, Verelst, L., Batjes, N., Dijkshoorn, K., Engelen, V. Van, Fischer, G., Jones, A., Montanarella, L., Petri, M., Prieler, S., Teixeira, E., Wiberg, D., Shi, X., 2009. Harmonized World Soil Database (version 1). Soil Sci. 38 https://doi.org/3123.
National Land Service under the Ministry of Agriculture, 2017. Dirv_DR10LT – spatial data set of soil of the territory of the Republic of Lithuania at scale 1:10 000 [WWW Document]. URL http://www.geoportal.lt/metadata-catalog/catalog/search/resource/details.page?uuid=%7B449450A9-AD8C-6E9E-6FCB-06A0584BF88C%7D (accessed 1.25.17).
National Land Service under the Ministry of Agriculture, 2009. SEŽP_0,5LT – digital spatial laser scanning points data of land surface of the Republic of Lithuania [WWW Document]. SE GIS-Centras. URL https://www.geoportal.lt/metadata-catalog/catalog/search/resource/details.page?uuid=%7B3AC99DBC-4C8A-F5B5-C859-

38EFF4E2DE60%7D (accessed 10.25.17).
National Land Service under the Ministry of Agriculture, 2001. Dirv_DR10LT – spatial data set of soil of the territory of the Republic of Lithuania at scale 1:10 000 [WWW Document]. URL http://www.geoportal.lt/metadata-catalog/catalog/search/resource/details.page?uuid=%7B449450A9-AD8C-6E9E-6FCB-06A0584BF88C%7D (accessed 5.12.18).
National Statistical Commettee of the Republic of Belarus, 2017. STATISTICAL YEARBOOK. National Statistical Committee of the Republic of Belarus.
Neitsch, S., Arnold, J., Kiniry, J., Williams, J., 2011. Soil & water assessment tool theoretical documentation version 2009. Texas Water Resour. Inst. 1–647. https://doi.org/10.1016/j.scitotenv.2015.11.063.
Olivera, F., Valenzuela, M., Srinivasan, R., Choi, J., 2006. Gis-swat: a geodata model and gis interface for swat 1. J. Am. Water Resour. Assoc. 77845.
Park, S., Bailey, R.T., 2017. SWAT-MODFLOW Tutorial: Documentation for preparing model simulations 55.
Pilipchuk, V., Korzun, A., Pilipchuk, V., Korzun, A., 2014. Nutrient loads to the Baltic Sea from Kaliningrad Oblast and transboundary rivers.
Rathjens, H., Oppelt, N., 2012. SWATgrid: an interface for setting up SWAT in a grid-based discretization scheme. Comput. Geosci. 45, 161–167. https://doi.org/10.1016/j.cageo.2011.11.004.
Rimkus, A., Vaikasas, S., 2012. Mathematical modeling of the suspended sediment dynamics in the riverbeds and valleys of Lithuanian rivers and their deltas. Water Pollut. 105–124. https://doi.org/10.13140/2.1.2508.6402.
Stonevičius, E., Rimkus, E., Štaras, A., Kažys, J., Valiuškevičius, G., 2017. Climate change impact on the nemunas river basin hydrology in the 21st century. Boreal Environ. Res. 22, 49–65.
Stuopis, A., Gregorauskas, M., Stock, J., Vilniaus, C., 2010. Formation of Groundwater Runoff in Nemunas RBD 45.
SWAT Literature Database for Peer-Reviewed Journal Articles [WWW Document], 2018. URL https://www.card.iastate.edu/swat_articles/ (accessed 6.18.18).
Trotochaud, J., 2014. WEPP/SWAT Future Climate Input File Generator : Instructions Manual A simplified process for obtaining future climate inputs for the WEPP or SWAT models.
Vigiak, O., Malagó, A., Bouraoui, F., Vanmaercke, M., Obreja, F., Poesen, J., Habersack, H., Fehér, J., Grošelj, S., 2017. Modelling sediment fluxes in the Danube River Basin with SWAT. Sci. Total Environ. 599–600, 992–1012. https://doi.org/10.1016/j.scitotenv.2017.04.236.
Vigiak, O., Malagó, A., Bouraoui, F., Vanmaercke, M., Poesen, J., 2015. Adapting SWAT hillslope erosion model to predict sediment concentrations and yields in large Basins. Sci. Total Environ. 538, 855–875. https://doi.org/10.1016/j.scitotenv.2015.08.095.
Wu, Y., Liu, S., 2014. Improvement of the R-SWAT-FME framework to support multiple variables and multi-objective functions. Sci. Total Environ. 466–467, 455–466. https://doi.org/10.1016/j.scitotenv.2013.07.048.
Wu, Y., Liu, S., 2012. Automating calibration, sensitivity and uncertainty analysis of complex models using the R package Flexible Modeling Environment (FME): SWAT as an example. Environ. Model. Softw. 31, 99–109. https://doi.org/10.1016/j.envsoft.2011.11.013.
Мельник, В., Яцухно, В., Денисов, Н., Николаева, Л., Фалолеева, М., 2017. Агроклиматическое зонирование территории Беларуси с учетом изменения климата. Minsk-Geneva.